The influence of building form on energy use, thermal comfort and social interaction

A post-occupancy comparison of two high-rise residential buildings in Singapore

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ABSTRACT: Two recently completed high-rise residential developments, located side-by-side in a neighbourhood in Singapore, are compared in a post-occupancy study. Both have near identical demographics, are exposed to the same microclimate, and constructed with a similar palette of materials. The primary difference is form. One has a high degree of porosity with inner voids that act as conduits for natural air flow and offer a sheltered space for social engagement. The other is more compact, less porous and has social spaces attached to the building's exterior. The study included surveys of residents, behavioural observations and environmental measurements. On three counts – self-reported energy use, thermal comfort and social interaction – the former appears to be more successful than the latter. Findings suggest that building form affects multiple outcomes at once. A form strategy that lowers energy use, for instance, can also improve social engagement. The implication of this socio-environmental approach to form-making is discussed in the context of high-density tropical typologies.
KEYWORDS: Building Form, Energy Use, Social Interaction, Thermal Comfort, Tropical Climate

1. INTRODUCTION

Building form is an important factor that shapes environmental performance. Form variables such as geometry, compactness and porosity play a key role in passive outcomes, such as shade, access to daylight and natural ventilation [1]. Passive design has long been a consideration at the drawing board, as this pertains to indoor comfort and energy demand [2], and more recently to overheating risk reduction [3,4,5]. In the tropical context, the emphasis on passive design and measured performance, as drivers of form-making, was first advocated by Malaysian architect, Ken Yeang, who applied it high-rise buildings in dense urban conditions [6]. His case for the *bioclimatic model* – which proposed form-features such as skyterraces and form-strategies like placement of service cores to reduce solar gains – was influential in the 80s and 90s in Southeast Asia, at a time when energy security was a concern [2]. With the advent of the Green movement in the 2000s, however, the question of performance was assigned to electro-mechanical solutions such as air conditioning. At this time, design firms like WOHA (Singapore) also began experimenting with new form typologies that could push the limits of passive design [7]. What is noteworthy about strategies by WOHA is that they merge the environmental and the social [8]. Gaps in buildings that facilitate airflow, for instance, are also the spaces for social gatherings.

2. BACKGROUND

In 2008, the Housing & Development Board (HDB) of Singapore commissioned two high-rise public housing developments (Figure 1) within the same neighbourhood. Both buildings, completed in 2015, have a near identical demographic breakdown, are exposed to a similar microclimate, and constructed with a similar palette of materials.

Figure 1: Building A (left) and Building B (right)

The primary difference is their approach to form. Building A (Figure 2), by architects WOHA

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(Singapore), has a significant degree of porosity – gaps in the façade that let natural airflow pass through the towers. There are 12 vertically distributed skyterraces (four per tower) that, with the sky roof, act as social spaces. An inner void that runs vertically through each tower accelerates air flow, and acts as a semi-outdoor buffer space that mediates between outdoor conditions and apartment interiors. Each apartment opens onto this inner void, with which it interacts socially and environmentally.

Building B (Figure 3), by comparison, is compact and less porous. It has six skybridges for its residents, and one skygarden above a multi-storey carpark. None of these, however, are fully sheltered, nor are they directly connected to the apartments.

WOHA has stated that the design goals for Building A are occupant comfort, lower energy demand and social engagement [8]. The designer of Building B has spoken of creating a community building in the Modernist vocabulary [9,10].

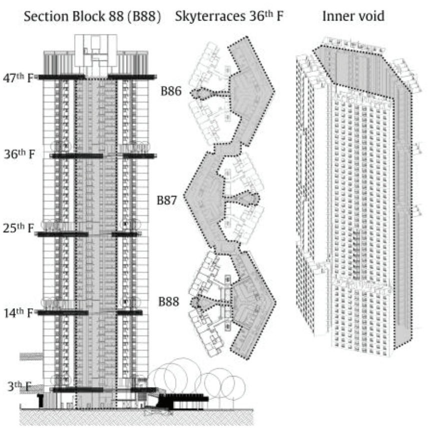

Figure 2: Building A showing section, floor plan with skyterraces and tower axonometric with inner void

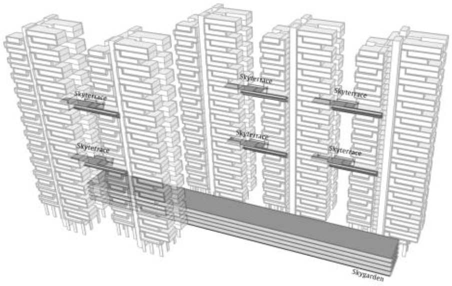

Figure 3: Building B axonometric showing skyterraces

This study set out to assess performance, as stipulated by the architects, and to gauge the extent to which performance can be linked to building form.

3. METHODOLOGY

The survey study began in August 2019 with residents of each building. Table 1 summarises the number of survey respondents in relation to the total number of apartments per building. This was augmented with behavioural observations, estimation of building form variables and environmental measurements.

Table 1: Population and sample size for each building.

Building	Nº of apartments	Nº of surveys	%
Building A	960	49	5.10
Building B	758	46	6.07

3.1 Survey

Surveys were carried out in the common areas of each building. Surveyees were randomly selected

On energy use, surveyees were asked: *'what is your approximate monthly electricity bill?' (Q1).* The options they were given were based on Singapore Power National Average Household Consumption for 2019 [11]. Surveyees were also asked *'do you have air-conditioning (AC) installed in your home?' (Q2)*, and '*at what time of the day is it usually turned on? (Q3)'*.

On use of social spaces, surveyees were asked *'do you visit the skyterraces in your estate?' (Q4).* If they answered 'yes', they were then asked: '*how often?' (Q5), 'how much time do you spend in them?' (Q6),* and *'why you visit them?' (Q7).* Additionally, residents were asked (on a Likert scale) if *'skyterraces (including roof) are used by their neighbours' (Q8).*

To gauge social interaction between residents, surveyees were asked *'how many neighbours in your estate are you friends with?' (Q9).* For this question, the answer options were '0-4', '5-9', '10-14', '15-19', '20-25' and '25-30'.

On the question of comfort, surveyees were asked *'in terms of thermal comfort, how do you generally feel in the skyterraces and roof of your estate?' (Q10).* They could answer from a 5-point thermal comfort scale, commonly used in comfort studies [12].

Each surveyee was asked his/her age, household size, floor level where s/he lives and how long s/he had been living in the development.

3.2 Building Form

The ratio of social space to total built-up area was calculated. The proportion of social areas in shade vs without shade was estimated. These calculations included both skyterraces and roofs above carpark. Another consideration was the percentage of building façade exposed to outdoor conditions. In Building A, the façade facing the inner void was deemed 'not exposed'. For Building B, the façade adjacent to circulation corridors, voids and staircases was likewise categorised 'not exposed'.

3.3 Behavioural Observations

Skyterraces in both buildings were visited every two hours from 14:00 until 18:00 (i.e. a total three times per afternoon) from August 6 to 9 and again, between August 12 to 14. During each visit, the number of visitors was counted. Counting was carried

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out in the afternoons since occupants were observed to visit skyterraces mostly during the afternoon and evening, as observed during surveys.

3.4 Measurement of Environmental Conditions

The air temperature (Ta) of skyterraces and outdoor conditions was measured for 6 days (July 25 – July 30, 2019). Air velocity (Va) was measured on day 1 and 2 of that same period, but only for Building A.

Only skyterraces linked to towers of buildings A and B were selected for temperature measurements (i.e. excluding social spaces on roofs of carparks). Three skyterraces on 14th, 25th and 36th storeys of Building A was selected, along with two on the 18th and 33rd storeys of Building B, which were at a similar height.

Readings were taken at 4pm, when the day was typically warmest. Reference 'outdoor' readings were taken on the roof of carparks of both buildings; the sensors here were sheltered from direct sun and placed less than 50 meters away from nearest skyterrace.

3.5 Statistical Analysis

Non-parametric statistical tests were carried out on data from the surveys. For Q1, Q8, Q9 and Q10 Mann-Whitney's two sample test was performed; for Q2 and Q3 Fisher's exact test; for Q4, Q5, Q6 and Q7 Pearson's Chi-squared test. The analyses were done with Rstudio software. Rstudio functions *chisq.test, fisher.test, wilcox.test and shapiro.test* were used, respectively.

Mann-Whitney's two sample test was used to compare measurements of buildings A and B.

4. RESULTS

Tables 2 and 3 summarise responses to survey questions. Table 4 summarises building form variables. Table 5 summarises mean values for each question and statistical significance (p-value) of the difference between the two buildings.

Table 2: Summary of responses to energy questions.

	Building A	Building B
Q1. What is your approximate monthly electricity bill?		
<$100 (SGD)	2 (6.5%)	1 (2.7%)
$50-$99 (SGD)	13 (41.9%)	11 (29.7%)
$100-$149 (SGD)	12 (38.7%)	13 (35.1%)
$150-$199 (SGD)	2 (6.5%)	7 (18.9%)
$200-$249 (SGD)	2 (6.5%)	5 (13.5%)
Q2. Do you have installed AC in your home?		
Yes	48 (98.0%)	45 (100%)
No	1 (2%)	0 (0.0%)
Q3. At what time of the day are they usually turned on?		
Morning	0 (0.0%)	0 (0.0%)
Afternoon	1 (2.4%)	0 (0.0%)
Evening	2 (4.8%)	0 (0.0%)
Night	43 (93.5%)	43 (97.7%)

Table 3: Summary of responses to social questions.

	Building A	Building B
Q4. Do you visit the skyterraces of your own estate?		
Yes (1)	46 (93.9%)	36 (78.3%)
No (0)	3 (6.1%)	10 (21.7%)
Q5. How often do you visit the skyterraces?		
Every day or many times a week	18 (39.1%)	5 (13.9%)
Once a week	13 (28.3%)	12 (33.3%)
Once or twice a month	15 (32.6%)	19 (52.8%)
Q6. How much time do you spend on them?		
< 30 minutes	18 (41.9%)	16 (44.4%)
>= 30 minutes	25 (58.1%)	20 (55.6%)
Q7. Why do you visit the skyterraces and roof?		
a. Socialize with neighbours	13 (30.2%)	7 (19.4%)
b. Look at the views	27 (62.8%)	16 (44.4%)
c. To take kids to play	10 (23.3%)	15 (41.7%)
d. To exercise	5 (11.6%)	19 (52.8%)
Q8. Are the skyterraces used by your neighbours?		
1 Yes, a lot	7 (14.9%)	5 (10.9%)
2 Yes, somewhat	26 (55.3%)	15 (32.6%)
3 Yes, but not so much	12 (25.5%)	20 (43.5%)
4 Not at all	2 (4.3%)	6 (13.0%)
Q9. How many neighbours in your estate are you friend with?		
0-9 neighbours	16 (35.6%)	16 (44.4%)
10-19 neighbours	8 (17.8%)	3 (8.3%)
20-29 neighbours	3 (6.7%)	1 (2.8%)
Q10. In terms of your thermal comfort, how do you generally feel in the skyterraces of your estate?		
+2 (very comfortable)	8 (16.7%)	3 (7.3%)
+1 (Comfortable)	36 (75.0%)	21 (51.2%)
0 (Neutral)	4 (8.3%)	13 (31.7%)
-1 (Uncomfortable)	0 (0.0%)	4 (9.8%)
-2 (Very uncomfortable)	0 (0.0%)	0 (0.0%)

Table 4: Summary of building form variables

	Building A	Building B
Skyterrace area (social space)		
Shaded	13,404 m² (63.2%)	582.6 m² (11.8%)
Unshaded	7,800 m² (36.8%)	4,352.2 m² (88.2%)
Total	21,204 m² (100%)	4,934.8 m² (100%)
Gross floor area [13]	111,106 m²	87,000 m²
Skyterrace as % GFA	19.1%	5.7%
Percentage of façade directly exposed to outdoor conditions		
Directly exposed	43.3%	53.6%

Table 5: Mean responses and statistical significances of the difference between Building A and Building B.

	Building A	Building B	p-value
Energy-related aspects			
Average self-reported electricity bill (Q1)	$107.3 (n=31)	$130.4 (n=37)	0.038 (*)
Average number of dwellings with AC (Q2)	98.0% (n=49)	100% (n=45)	0.477
Average number of dwellings that turn on AC at night (Q3)	93.5% (n=46)	97.7% (n=44)	0.085 (.)
Social aspects			
Average number of neighbours that residents consider as friends (Q9)	10.2 (n=27)	7.5 (n=20)	0.0710 (.)
Average percentage of residents visiting skyterraces (Q4)	93.9% (n=49)	78.3% (n=46)	0.002 (**)
Average percentage of residents visiting skyterraces every day or many times a week (Q5)	39.1% (n=46)	13.9% (n=36)	0.000 (***)
Average percentage of residents that spend more	58.1% (n=43)	55.6% (n=36)	0.886

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than 30 minutes on skyterraces (Q6)			
Average likelihood of neighbours visiting skyterraces, in Likert scale (Q8)	2.19 (n=47)	2.59 (n=46)	0.008 (**)
Average thermal comfort in skyterraces, in a 5-point thermal comfort scale (Q10)	+1.07 (n=48)	+0.53 (n=41)	0.000 (***)
Environmental conditions			
ΔT (Ta outdoor – Ta skyterrace)	1.39ºC (n=6)	0.78ºC (n=6)	0.003 (**)
Air temperature at skyterrace	29.65ºC (n=6)	29.81ºC (n=6)	0.189
Air temperature outdoors	31.04ºC (n=6)	30.59ºC (n=6)	0.115
Air velocity at skyterrace	1.39m/s	-	-
Significance codes: >0.1 (.) < 0.05 > (*) < 0.01 > (**) < 0.001 > (***)			

4.1 Survey

Analysis of data suggests that the two groups, Building A vs Building B, are not statistically different for any background variable. Normality is not found in their answers either.

On energy use, the reported electricity bill of surveyees in Building A is lower than Building B by almost $23**.** Building A has a mean of $107.3; Building B, $130.4. This finding has statistical significance. *Note: data is filtered to surveyees between 19 and 59 years of age, who are more likely to be aware of the monthly bills.*

On use of AC, even though the two buildings are not significantly different in ownership of AC, approximately 93% of those from Building A say they use AC at night compared with almost 98% in Building B. This finding is marginally significant. *Note: the analysis is filtered for surveyees who say they use AC at night since this represents over 90% of responses in both buildings.*

On use of skyterraces, 94% of surveyees from Building A say they visit skyterraces, which is found to be significantly higher than 78% of surveyees from Building B. Additionally, skyterraces in A are visited more frequently than in B, with approximately 39% of surveyees in former saying *'every day or many times a week'* compared with 14% in the latter. The perception of neighbours visiting terraces in Building A tends towards 'yes, somewhat'; in Building B it is closer to 'yes, but not so much'.

On why skyterraces are visited, 30.2% in Building A say 'socialise with neighbours' compared with 19.4% in Building B. The finding is not statistically significant.

Regarding social interaction, surveyees in Building A say that they consider, on average, 10.2 neighbours as friends in comparison to surveyees on Building B who consider 7.5 neighbours as friends. The difference is marginally significant. *Note: analysis is limited to those who say 'yes' to visiting skyterraces and say they spend more than 30 minutes per visit, so as to eliminate those who are just passing through.*

On perceived thermal comfort, 91.7% of surveyees in Building A say they feel 'very comfortable' or 'comfortable'; in Building B, the figure is 58.5%. The mean answer on the comfort scale is +1.07 for Building A (i.e. towards greater perceived comfort); the mean answer for Building B respondents is 0.53 (i.e. towards neutrality).

4.2 Building Form

Building A has four times more surface area for skyterraces than B: 21,204 m^2 and 4,935 m^2, respectively. As a proportion of total built up area, skyterraces in Building A account for 19.1%; Building B, 5.7%. In Building A, the surface area of skyterraces that is shaded is 63.2%; in Building B, 11.8%. The percentage of facade in A that is exposed to outdoors is 43%; in B it is 54%

4.3 Behavioural Observations

Skyterraces in Building A account for 257 visitors during the period of measurement; Building B, 60 (Table 6). Normalised against number of households, Building A has higher visitorship per household.

Table 6: Counting of people visiting skyterraces per building during period of observations (6-9, 12-14 August)

Building	Number of people on skyterraces	Number normalised against number of households
Building A	257	0.27 per household
Building B	60	0.08 per household

4.4 Environmental factors

The mean Ta of Building A is 0.16ºC lower than that in B. This difference is not statistically significant. Measured outdoor temperatures at both buildings are not significantly different and are highly correlated (R = 0.92). However, the mean ΔT in A is almost 1.4ºC (14^{th}F: 0.99ºC, 25^{th}F: 1.41ºC, 36^{th}F: 1.79ºC), while in B ΔT mean is almost 0.8ºC (19^{th}F: 0.67ºC, 33^{th}F: 0.89ºC). The difference between the two is statistically significant. A mean air velocity of 1.85 m/s is measured in Building A (14^{th}F: 2.26 m/s, 25^{th}F: 1.82 m/s, 36^{th}F: 1.48 m/s).

5. DISCUSSION

The architects for Building A, WOHA, have said they seek, through design, three outcomes: improved occupant comfort, lower energy use, and greater social interaction [8,14]. The findings from this study suggest that Building A does better on all three counts than Building B. *However, in what ways can the success of Building A be linked, directly or indirectly, to its built form?*

The distinguishing feature of Building A is its inner core – made up of voids and skyterraces – that acts as a conduit for natural air-flow and holds spaces for social interaction. As a result of this core, parts of the building envelope are inward facing. By contrast,

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Building B is compact, without voids or inner facades. Its skyterraces are fewer and affixed to its façade, and therefore more exposed to outdoor conditions.

The first *form* hypothesis relates to comfort in skyterraces. The sheltered skyterraces of Building A should fare better in terms of thermal comfort than the exposed ones in Building B. The findings from this study support this. There is a measurable difference in the mean thermal comfort response of the two groups: +1.07 for A versus +0.53 for B, i.e. the former is more comfortable than the latter. This is corroborated by temperature and air velocity readings. In Building A, ΔT between skyterraces and outdoors is 1.39ºK, almost twice the ΔT in Building B. The mean Va in Building A voids is approximately 1.9 m/s. Lower temperatures and elevated air speeds should lead to high perceived comfort.

It is likely that comfort is a variable affecting visitor preferences. In Building A, where comfort levels are higher, 94% of those surveyed say they visit skyterraces; in Building B, only 78%. Thirty-nine percent in Building A also say they visit *'every day or many times a week'* compared with 14% in B. These findings appear to align with observed visitor numbers: skyterraces in A have 257 visitors versus 60 in B. Normalised against the number of households, skyterraces in Building A (0.27) appear to be more popular than in B (0.08), assuming all observed visitors are residents of the same building. It should be noted there are other reasons for visitorship. The survey suggests 'view' is a factor. Skyterraces in Building A are also substantially bigger than the ones in Building B, with room for more people.

The second *form* hypothesis relates to social engagement: residents of Building A, who visit skyterraces more frequently, ought to know more neighbours. This is supported by the findings: surveyees from Building A say they know an average 10.2 neighbours, compared with 7.5 in Building B, i.e. 36% more. The difference is found to be marginally significant.

The third *form* hypothesis relates to energy use. Lower temperatures and higher air flows in the central void of Building A are likely to affect energy use. Apartments that open onto this cooler core can divert air flow through their living spaces, thereby reducing the need for mechanical cooling. Inner facades, opening onto a cool void, are likely to transmit lower solar heat gain into the apartments.

The findings show a difference in energy use. The monthly energy bill is 17% lower in Building A ($107.3) than in Building B ($130.4), notwithstanding identical ownership of air conditioners between the groups. Several variables that might affect energy consumption can be ruled out. Both buildings have near identical demographics; they rely on a similar palette of materials and comply with the same regulatory limit for Residential Envelope Transfer Value (RETV) of 25 W/m^2 [15].

From this study, it is evident that Buildings A and B are two distinct form typologies. Findings suggest that form is a likely factor affecting performance in multiple ways. The significance of these findings become clearer when they are extrapolated to the urban scale. Singapore has 1 million HDB flats [16]. If the entire stock of housing were to perform at the same level as Building A, i.e. spending 17% less on energy, the impact at the city scale would be a saving of 729 GWh/year, based on a total of 4,287 GWh consumed in 2017 by public households [17,18]. This is equivalent to a reduction of 0.305 million metric tons of equivalent CO_2 emissions, based on Singapore's 2018 Grid Emission Factor of 0.4188 kg CO_2/kWh [17]. If every HDB household were to also interact with 36% more neighbours, is likely that social capital of the city would increase. Social capital is defined as the number of relationships between people in group that leads trust and cohesion [19].

6. CONCLUSIONS

Thermal comfort, energy use and social interaction are complex outcomes, affected by many variables. In this study, building form is found to be a factor that contributes to each outcome in direct and indirect ways. In Building A, the presence of sheltered and comfortable social spaces appears to lower barriers to neighbourly interactions. The inner void and skyterraces act as a nexus of social interaction. The core also affects the energy performance of the apartments. What is seen in Building A, therefore, can be described as the integration of social and environmental objectives through form-based solutions.

Architects and researchers in the tropical regions have in the past argued for the importance of form features and strategies, such as open-to-sky courtyards and sunshades, however, primarily for social or place-making purposes [20, 21]. The notion that a form-based design approach can simultaneously affect multiple outcomes in high-rise typologies is rare. Architect Ken Yeang made a case for this in the 80s and 90s, applying the bioclimatic model to office buildings in Malaysia which were said to deliver better energy performance and occupant comfort. Two noteworthy buildings of that era were evaluated in a study, with surveys and energy audits, that revealed them to be unsuccessful in both regards [2]. This was attributed to an inconsistent application of bioclimatic principles and to the underestimation of comfort expectations and preferences.

WOHA's approach to form, represented by Building A, differs from these earlier experiments in two ways. It sees environmental performance and social engagement as interdependent outcomes. The

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building also creates an onsite microclimate with sheltered inner voids. These spaces are more comfortable; they also reduce thermal load and enhance the potential for cross ventilation. This form strategy is seen in other WOHA projects like the School of the Arts and Oasia Hotel Downtown [8,14] and in some of Yeang's more recent projects such as the National Library in Singapore [22].

Cities across the globe struggle to address environmental goals and social goals, which are sometimes at odds. Singapore offers lessons on integration in the high-density tropical context [23]. In this study, Building A demonstrates how this idea can be advanced further with form-based solutions at the building scale. Lessons learnt here are particularly relevant to developing countries where capital investment and access to technology are limited.

The limits of the current study should be countered in future research by increasing survey sample sizes and accessing actual energy bills. It should consider other factors that influence thermal comfort such as radiant temperature, relative humidity, activity level, and clothing. In the Singapore context, it would be necessary to compare Buildings A and B, both relatively new, with earlier generations of public housing typologies, which had different sizes and arrangements of social space.

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